The Effects of Flood-induced Lane Reduction on the Capacity of a Road Network

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The Effects of Flood-induced Lane Reduction on the Capacity of a Road Network

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Abstract: *Flooding can severely disrupt transportation infrastructure. Existing models for assessing flooding's impact on road transport often assume all lanes remain open, which contradicts actual observations. This study examines the impact of flood depth on road capacity and traffic conditions, aiming to enhance flood-based traffic models by analyzing the relationship between flooding and the Macroscopic Fundamental Diagram of Traffic. Fifteen (15) 30-minute video clips of flooded roads from the CCTV archive of the Metro Manila Development Authority (MMDA) were analyzed. Analysis of these videos showed that flood depths over 25 cm consistently caused lane closures. Moreover, empirical data from 433 samples revealed a significant reduction in vehicle flow, decreasing by 40% to 70% per lane kilometer as lane closures increased. These findings underscore the substantial impact of flood-induced lane closures on traffic flow and can be used as reference for future flood-based traffic models.*

Keywords: Flooding, Lane Closure, Road Capacity, Modelling

1. INTRODUCTION

The modern world depends on a vast network of interconnected infrastructure, with transportation being the most crucial system as it supports all other lifeline systems [1-2]. Disruptions to transportation, often caused by natural hazards, such as floods, snow, volcanic eruptions, and earthquakes, can hinder the repair of other critical infrastructure and damage socioeconomic networks [3]. Traffic data from disasters like the Great East Japan Earthquake show severe reductions in vehicle speeds, causing gridlock and impeding evacuation and response [4].

Flooding, being frequent and instantaneous, is considered the costliest natural hazard in terms of human life and property damage [5]. It poses significant risks to transportation infrastructure, especially in urban areas where intense precipitation and impervious surfaces increase surface runoff and flooding [6]. Urban flooding can submerge or render impassable about 40% of a city's road network, leading to reduced accessibility, longer travel times, and increased travel distances [7].

Recent flood-based traffic models have begun to include flooded road segments with an assumed reduced capacity due to floods, rather than outright assuming that the roads are closed [8-11]. These models commonly assume that all lanes are open with road capacity being an assumed variable percentage decrease dependent on flood depth. However, observations from [12] show that lane closures are a common occurrence brought about by flooding, and the likelihood of lane closures escalates as flood depths increase. This decrease in the number of lanes then results in the decreased road capacity. Despite this, no study has provided a robust empirical basis for the percentage change in road capacity due to lane closures caused by varying flood depths. Thus, there is a gap in understanding the effects of flooding on road capacity.

Conducting an in-depth study to precisely identify this parameter under different flood scenarios will greatly improve the creation of flood-based traffic models. The primary objective of this research is to understand how flooding impacts traffic conditions. Specifically, the study aims to establish the relationship between flood depth and road capacity and to analyze the effects of flooding on the Macroscopic Fundamental Diagram of Traffic Flow (MFD). This comprehensive approach seeks to provide a clearer understanding of how flooding disrupts transportation systems and to lay the groundwork for future flood-based traffic models.

2. STUDY AREA

Metro Manila, the capital region of the Philippines, is located at the northern end of the country, approximately 14.6° north latitude and 121.0° east longitude. The city's tropical and maritime climate results in high temperatures, humidity, and abundant rainfall, with an average annual precipitation of 2,450 millimeters, leading to recurring urban flooding since the 19th century [20-21]. A previous study [13] found that intense rainfall (30-70 mm/hr.) can cause knee-deep or waist-deep flooding on major roads, paralyzing traffic and costing the economy around 2.4 billion pesos ($48 million) per day due to wasted gasoline and lost productivity. Similarly, [14] estimated that flooding results in an economic loss of 297 billion pesos during a 5-year flood event, with an annual probability of occurrence of 20%.

Numerous flood control initiatives have been implemented in Metro Manila, with over 5,000 projects ongoing, including drainage system expansions and trash clean-up operations [15-16]. Despite these efforts, the recent Typhoon Gaemi, locally known as Carina, heavily impacted Metro Manila. Combined with the southwest monsoon, it brought heavy rainfall, leading to widespread flooding in the region and nearby provinces [17-18]. The typhoon caused the overflow of La Mesa Dam, flooding low-lying areas and highlighting ongoing challenges in flood control [19].

The study by [13] identified flood-prone streets in Metro Manila, forming the basis for pinpointing key flood-prone areas. This data was cross-checked was cross-checked with the available CCTV locations of the Metro Manila Development Authority (MMDA). From this, the study focused on 15 roads within Metro Manila, each varying in road hierarchy (primary or secondary) and flow (free-flow or intersection), as depicted in Fig. 1. Thirty-minute videos were sourced from the MMDA's CCTV footage archive, covering the period from September 2023 to October 2023. These cameras, strategically positioned at elevated vantage points like tall buildings or traffic light poles, provided a bird's-eye view of major intersections and thoroughfares. Copies of both flooded and non-flooded footage, captured on identical days of the week and within the same timeframes, were obtained for analysis. This footage served as the primary data source for the study.

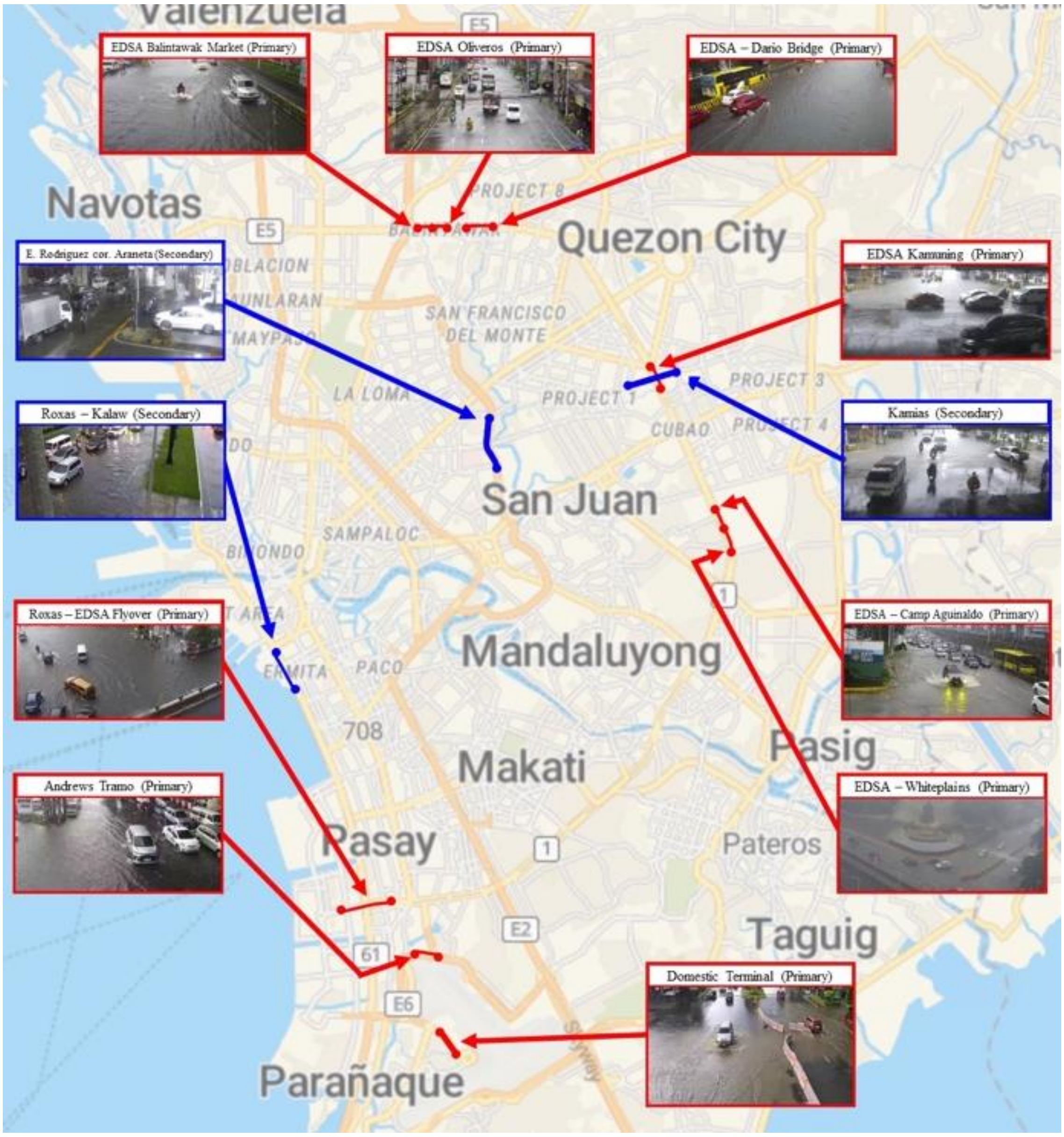

Fig. 1. Observed roads and their location on the map

3. METHODS

3.1 Data Collection

Using Google Maps, numerous road information was collected. The number of lanes for each road was determined based on the images provided by Street View. However, exclusive vehicle lanes, such as the bus lanes on Epifanio de los Santos Avenue (EDSA), were not included in the lane count. According to [22], dedicated lanes cater to one type of vehicle and operate under different rules and priorities, allowing them to avoid congestion. This segregation means that these lanes do not align with the traffic dynamics of adjacent lanes. Therefore, to create a more coherent dataset, only general-purpose lanes were considered. For this study, exclusive lanes are defined as those separated from other lanes by physical barriers or regulatory measures. Exclusive lanes without a physical barrier, such as bike lanes sharing space with other vehicles, were classified as general-purpose lanes because vehicles in them are still subject to external influences. Table 1 presents the number of lanes and the presence or absence of exclusive lanes for each road studied.

Determining and comparing road traffic conditions under different scenarios involved measuring segments of each road using Google Maps' Measure Distance feature. Two identifiable landmarks, such as streetlights, pedestrian overpasses, or columns of elevated transit lines, were selected to ensure precise measurements. The distance between these landmarks represented the road segment covered by a vehicle and served as the basis for analyzing traffic conditions (see Fig. 2).

Table 1. Lane details per road

Road Name	Number of Lanes (per Direction)	Bus lane	Bike lane
EDSA - Balintawak Market	5	✓	x
EDSA - Camp Aguinaldo	5	✓	✓
EDSA - Dario Bridge	5	✓	x
EDSA - Oliveros NB	5	✓	x
EDSA - White Plains	4	✓	✓
MIA Domestic Terminal 2 (NB)	3	x	x
MIA Domestic Terminal 2 (SB)	3	x	x
Roxas - EDSA Flyover	5	✓	✓
Andrews - Tramo	3	x	x
EDSA - Kamuning (NB)	3	x	x
E. Rodriguez (EB)	4	x	x
E. Rodriguez (WB)	4	x	x
Kamias (EB)	2	x	x
Kamias (WB)	2	x	x
Roxas - Kalaw	5	x	x

Fig. 2. Distance covered by vehicles as measured through Google Maps

To assess the effects of varying flood depths on road traffic conditions, maximum flood depths for each road were estimated using the MMDA Flood Gauge, as illustrated in Fig. 3 [23]. Water levels were converted from inches to centimeters, and maximum water levels for each road were approximated by gauging the height of the water against MMDA's classifications. Flood depth at the most submerged section of the road was assessed at five-minute intervals, with the highest recorded flood depth identified as the maximum depth for that road segment.

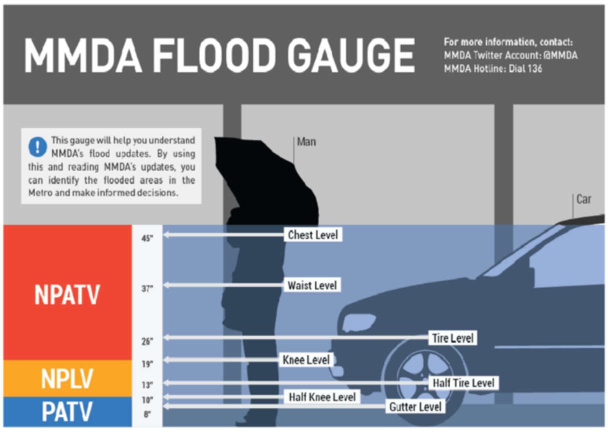

Fig. 3. MMDA flood gauge [23]

3.2 Video Analysis

Vehicle density was determined through the number of vehicles occupying a certain length of the road. A manual count of vehicles was done every 30 seconds. At intersections, the 30-second counting periods were initiated just before the traffic light turned red. Fig. 4 illustrates this process, based on a video footage captured on EDSA - Camp Aguinaldo, where density (in PCU/km/lane) denoted as D was computed using the following formula:

$$D = \frac{\frac{v}{d} \times 1000}{n}$$

Wherein,
v = Vehicle volume of road segment (PCU)
d = Distance covered (m)
n = Road segment's number of lanes (lane)
1000 = Used for Conversion (m to km)

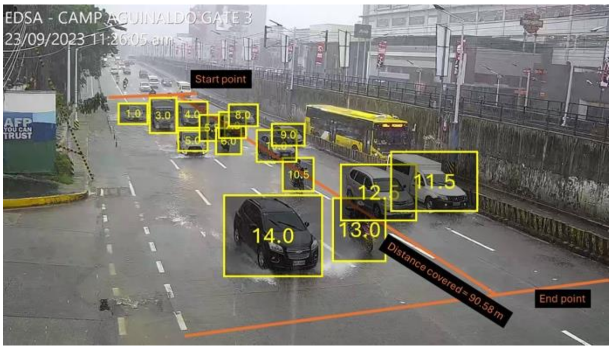

Fig. 4. Number of vehicles traveling on the road segment between sections X and Y

It should be noted that the vehicle counts were converted to their Passenger Car Unit (PCU) using the Passenger Car Equivalent Factors (PCEFs) supplied by [24]. Table 2 presents the PCEFs for each vehicle.
Similarly, flow rate was determined through a manual count of number of vehicles passing a point on the road within a given period. Fig. 5 illustrates this process, based on a video footage captured on EDSA - Camp Aguinaldo, where flow (in PCU/hr/lane) denoted as F was computed using the following formula:

$$F = \frac{\frac{f}{t} \times 3600}{n}$$

Wherein,
f = Vehicle volume of road segment (PCU))
t = Elapsed time (s)
n = Road segment's number of lanes (lane)
3600 = Used for Conversion (s to hr)

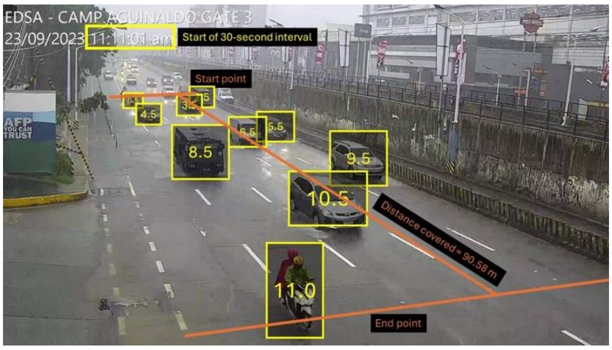

Fig. 5. (a) Number of vehicles traveling on the road segment at the start of the 30-second interval

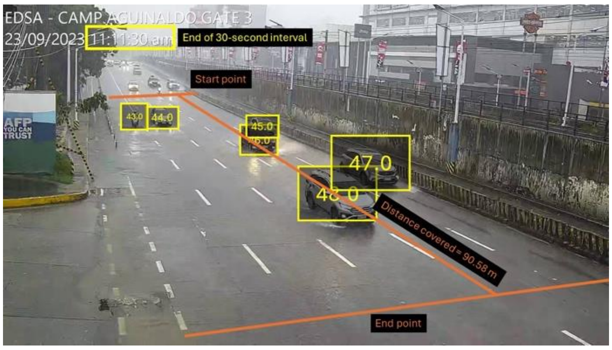

Fig. 5. (b) Number of vehicles traveling on the road segment at the end of the 30-second interval

Table 2. PCEF for the vehicles studied [24]

Classification	Vehicle Type	PCU
Private	Passenger Car	1.0
	Motorcycles	0.5
	Passengers and Goods Utility and Small Bus	1.5
	Rigid Truck, 2 Axles	2.0
	Trailer Truck 3+ Axles	2.5
	Non-motorized (Bicycles)	0.5
	Trailer Trucks	2.5
Public	Public Utility Jeeps (PUJ)	1.5
	Utility Vehicle (UV) Express	1.5
	Bus	2.5

The nature of this counting method introduces a number of measurement uncertainties. For example, some vehicles may be obscured by larger ones due to camera positioning, thus leading to minor discrepancies. To ensure inter-reliability, multiple observers were used to conduct the counts simultaneously. Each observer recorded the number of vehicles independently, and their counts were then compared. The average of these counts was then used as the value for the corresponding 30 seconds. Minor differences between the manual and automated counts were expected due to the inherent variability in human observation. However, these differences were generally small, and the overall set of observations compared well to other sources of data, affirming the method's reliability and accuracy.

The study prioritized ethical considerations given the use of CCTV footage, which captured images of numerous unidentified individuals and vehicles. All data were collected anonymously. Access to the data was limited to the research team, and strict data management protocols were followed to ensure secure storage, backup, and protection against unauthorized access.

4. RESULTS & DISCUSSION

4.1 Lane Closure

flood depths on the number of lane closures. The relationship between the observed number of lane closures relative to the maximum flood depth present on the road is shown in Fig. 6. It should be noted that there is no formal indication of a lane closure happening in the observed videos. Instead, lane closure, for the purpose of this study, refers to general-purpose lanes that are typically avoided by vehicles with lower ground clearance.

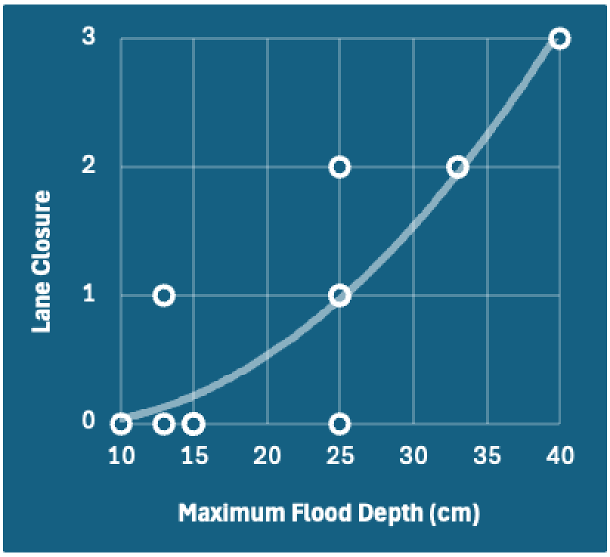

Fig. 6. Relationship of maximum flood depth with number of lane closures

From the figure, low flood depths (less than 25 cm) generally did not cause any lane closures. Lane closures typically began at a minimum flood depth of 25 cm, leading to at least one lane being closed. The number of lane closures increased with flood depth, reaching a peak of three lane closures at a maximum flood depth of 40 cm. These findings indicate that the impacts of flooding on the transportation network can start to become significant at a flood depth of at least 25 cm and worsen as flood depth increases. However, there are some outliers in the data which suggest that the general layout of the road may also have external effects on the number of lane closures. For instance, at certain points where the flood depth is less than 25 cm, there were instances of lane closures. This indicates that factors such as road design, drainage capacity, and surrounding infrastructure may influence the extent of lane closures even at lower flood depths.

A closer look at footage from EDSA - Dario Bridge shows that flooding has surpassed the gutter level, resulting in an estimated maximum flood depth of 40 cm (see Fig. 7). These elevated water levels have closed two lanes from the original five-lane configuration. Additionally, some vehicles have stalled or parked in the leftmost lane to avoid the floodwaters, reducing the available number of lanes by one and further impeding traffic flow. These observations align with the findings of [7, 12, 25], who noted that floodwaters can render roads inaccessible or difficult to navigate, causing vehicles to stall or leading to lane closures.

Furthermore, due to the road layout, most vehicles approach from the rightmost side (see Fig. 7). However, the presence of floodwaters deters vehicles from passing through, as the depth and unpredictability of the water pose safety risks and potential damage to vehicles. Consequently, drivers tend to avoid flooded lanes, effectively treating them as closed. This behavior initiates a cascading effect, with vehicles merging into other lanes to avoid the flooded area. This sudden influx of merging vehicles creates congestion, disrupts traffic flow, and reduces the overall capacity of the road network. As highlighted by [26], lane changes can significantly bottleneck overall traffic flow, increasing the likelihood of capacity drop and jam density.

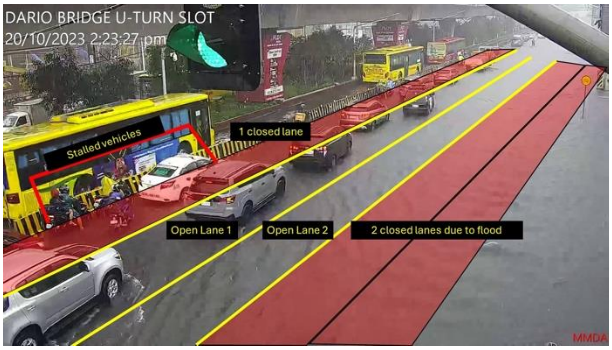

Fig. 7. Flooded EDSA-Dario Bridge road segment from CCTV footage and its number of open and closed lanes

4.2 Road Capacity

A dataset comprising 433 vehicle samples from actual flood events was examined to investigate the correlation between vehicle flow and the number of lane closures, as depicted in Fig. 8. The data points illustrate the average vehicle flow per kilometer per lane.

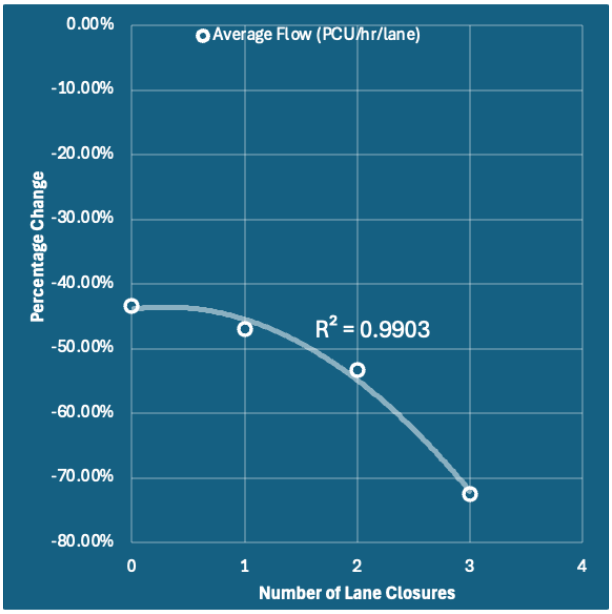

Fig. 8. Relationship of number of lane closures with change in lane capacity

Based on graph, it is evident that the flow rate decreases as the number of lane closures increases, showing reductions ranging from 40% to 70% at higher flood depths. As discussed previously, higher maximum flood depths lead to fewer usable lanes. This reduction in lanes increases the density of vehicles on the remaining operational lanes. With fewer viable lanes, more vehicles are compelled to merge onto a reduced number of lanes, resulting in higher vehicle concentration. This heightened density causes significant congestion, thereby slowing down the overall flow rate of traffic. The restricted movement and increased stop-and-go conditions further contribute to the diminished flow rate, as vehicles struggle to maintain consistent speeds or maneuver freely. Additionally, the graph has an R-squared value of 0.9903. This high R-squared value indicates a strong correlation between lane capacity and the number of flooding scenarios, reinforcing the findings that lane capacity directly changes depending on the number of lane closures due to flooding.

It should be noted that adjustments were made to the lane count to ensure a more precise depiction of traffic conditions. Firstly, to account for lane splitting, 0.5 was added to the number of lanes whenever lane splitting was evident in the video footage. Lane splitting, a common practice among Filipino motorcycle riders, involves maneuvering between lanes of slow-moving or stopped traffic, as shown in Fig. 9. This practice becomes even more prevalent under flooding conditions due a higher likelihood of a build-up of vehicles. Furthermore, vehicles capable of traversing higher flood depths and thereby avoiding congestion in minimally flooded lanes were excluded from the count (see Fig. 10). These vehicles operate under different rules and priorities, similar to those in exclusive lanes, which cater to specific vehicles and are not subject to the same dynamics as those in adjacent lanes. These help to more accurately represent the actual traffic conditions of the road.

Fig. 9. Motorcycles practicing lane splitting

Fig. 10. Disregarded vehicles traversing closed lanes

However, this study did not find a direct correlation between maximum flood depth and flow rate. Instead, it draws from the findings of [12], which show that higher flood depths always lead to an increased number of closed lanes, while [11] further describe that higher flood depths will increase density and decrease flow. Higher flood depths affect flow rate, which in turn affects the road's capacity. Fig. 11 shows the relationship between the curves presented in this paper. According to the established patterns of traffic congestion during flood conditions, the graph shows that as flood depths increase, lane closures that follow force more vehicles into fewer lanes, resulting in a reduced flow rate. Comparing this with the assumptions of [8], they significantly underestimated the reduction in capacity at low flood depths, assuming a mere 10% decrease. However, empirical data indicated a much larger reduction, approximately 40%. These results are more consistent with the research done by [9], who observed a roughly 50% decrease in flow rate at low flood depths and an even more substantial reduction of around 75% at higher flood depths. This discrepancy underscores the critical need for precise assessments of flooding's impact on road capacity to enhance traffic models.

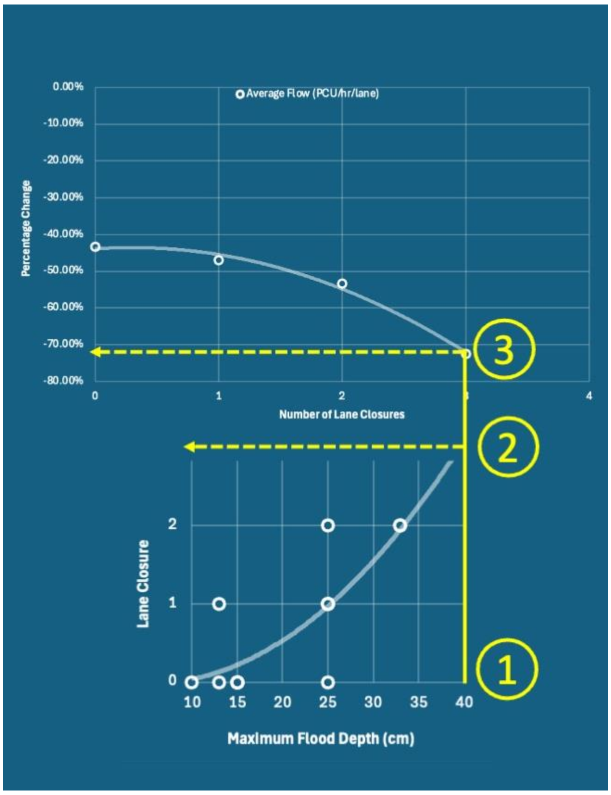

Fig. 11. Relationship of maximum flood depth with change in lane capacity

4.3 Macroscopic Fundamental Diagram

Fig. 12 shows the correlation between the number of lane closures due to flooding and the deterioration of the MFD, which captures the overall traffic flow and density of a road network. From the graph, it could be observed that, as lane closures increase, the efficiency and reliability of the network degrade, leading to more pronounced changes in the MFD shape.

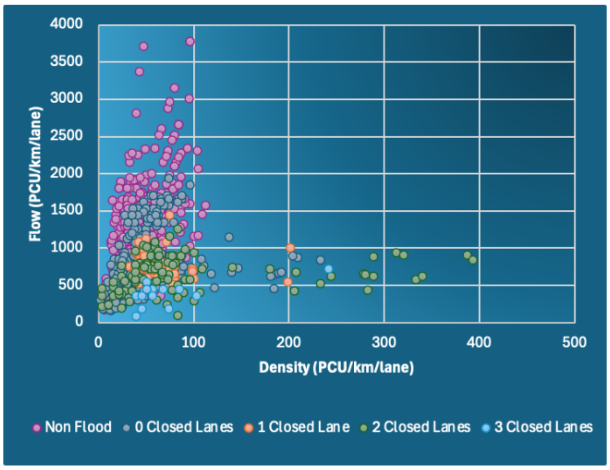

Fig. 12. Relation of density and flow under varying lane closures

Under dry conditions, the road network maintains a stable and predictable MFD shape, reflecting efficient and reliable traffic operations. However, even with one or fewer lane closures, there is a noticeable change in the MFD shape compared to dry conditions. While this change is less abrupt, it still signifies a clear alteration in traffic density and flow. This can be attributed to the presence of flooding, which disrupts normal traffic patterns and reduces the network's capacity to handle the usual volume of vehicles. Flooding, even with minimal lane closures, introduces obstacles such as water accumulation, which can slow down traffic and increase travel times. Drivers may also exhibit more cautious behavior, leading to altered flow dynamics. These factors collectively contribute to changes in the MFD shape, highlighting the sensitivity of the road network to even minor flood-related disruptions. When lane closures increase to two or more, the network's capacity to manage traffic efficiently is significantly compromised. The reduction in available lanes leads to higher congestion levels, longer travel times, and increased variability in traffic conditions. This results in a more scattered MFD shape, indicating less predictable and more unstable traffic operations. The network's resilience diminishes as it becomes harder to reroute traffic effectively, causing bottlenecks and flow breakdowns.
The findings by [22] further explain this phenomenon. They observed that varying flood depths have a substantial impact on the MFD shape. At higher flood depths, particularly those exceeding 30 cm, the negative effects on the MFD are most severe. This is because such flood levels not only cause extensive lane closures but also pose physical barriers that disrupt traffic flow. Vehicles may be forced to slow down significantly or stop, leading to a sharp decline in network performance and a dramatic increase in traffic instability.

4.4 Significance of Changes in Road Capacity Under Flood Conditions

Road capacity is a critical factor in traffic modeling, influencing how efficiently a transportation network operates under various conditions. Observations indicate that lane closures, commonly brought about by flooding, escalate as flood depths increase, thereby decreasing road capacity. Despite this, no study has empirically quantified the percentage change in road capacity due to varying flood depths, leaving a gap in understanding these effects. The percentage changes identified in this study could be applied to future flood-based traffic models to dynamically adjust road capacity based on simulated flood conditions, enabling planners to predict traffic bottlenecks, congestion patterns, and overall network performance more precisely. This, in turn, supports measures to mitigate economic impacts, develop more effective mitigation strategies, optimize evacuation routes, and improve the resilience of transportation networks to flooding events.

5. CONCLUSION

supports all other critical infrastructures. Disruptions from natural hazards like floods can severely impact socioeconomic networks and hinder the repair of other infrastructures [1-3]. Flooding, particularly in urban areas, is a major concern due to its frequency and substantial impact on road networks, reducing accessibility and increasing travel times [5-7]. Recent flood-based traffic models have started to include flooded road segments with assumed reduced capacity due to floods rather than assuming complete road closures [8-11]. However, these models commonly assume that all lanes are open, with road capacity being an assumed variable percentage decrease dependent on flood depth. Observations by [12] show that lane closures are a frequent occurrence during flooding, and the likelihood of such closures increases with flood depths, leading to a decrease in road capacity. This highlights a gap in understanding the effects of flooding on road capacity. To address this, the study aimed to establish the relationship between flood depth and road capacity and analyzed the effects of flooding on the Macroscopic Fundamental Diagram of Traffic Flow to improve flood-based traffic models.

The analysis of 15 videos revealed that vehicles that perceive floodwaters to be high tend to avoid these sections of the road, effectively treating them as closed lanes. This behavior reduces the effective size of the road as vehicles are more squeezed into the remaining lanes. A quantitative look at the findings shows that flood depths exceeding 25 cm consistently led to lane closures, increasing in severity up to three closures at a maximum depth of 40 cm. Moreover, empirical data from 433 flood events demonstrated a significant reduction in vehicle flow—by 40% to 70% per lane kilometer—as lane closures increased. While no direct correlation was found between maximum flood depth and flow rate, indirect relationships were observed, consistent with previous studies. These findings highlight the disruptive impact of flood-induced lane closures on traffic flow, evident in alterations to the MFD even with minimal closures. With two or more closures, network capacity is markedly compromised, exacerbating congestion and necessitating adaptive strategies to mitigate traffic disruptions during flood events.

Overall, results suggest that several strategies could be employed to mitigate the impact of flooding on road capacity. One critical approach is improving urban drainage systems, ensuring they are capable of handling increased rainfall and reducing water accumulation on roads. Incorporating green infrastructure, such as permeable pavements, green roofs, and bioswales, can significantly enhance water absorption and decrease surface runoff. Additionally, elevating roadways and critical infrastructure in flood-prone areas can prevent waterlogging and maintain road functionality during floods. Implementing advanced flood prediction and monitoring systems can provide timely warnings, allowing for preemptive traffic management and road closures to minimize congestion and ensure safety.

To advance future studies, researchers suggest broadening the geographic range and enhancing data collection efforts to encompass a variety of urban areas. This method could provide more extensive insights into diverse traffic behaviors and conditions across different regions. Moreover, with the increasing prevalence of active transportation modes like walking and cycling, future research could examine the impact of flooding on these forms of transport to offer a more comprehensive view of flooding's overall effect on urban mobility [27-28]. This would ensure that infrastructure and policy measures address the needs of all road users, thereby enhancing resilience and safety for everyone during flood situations. Overall, this study represents an initial step in assessing the capacity reduction of road networks during flood-induced lane closures, setting a precedent for similar urban areas globally.

6. ACKNOWLEDGEMENTS

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